

# Dark matter and the LHC

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Cosmological and astrophysical measurements indicate that the universe contains a large amount of dark matter. A number of weak scale dark matter candidates have been proposed in extensions of the standard model. The potential to discover the dark matter particle and determine its properties at the upcoming LHC is summarized.

## 1. INTRODUCTION

There is strong evidence coming from various scales that dark matter (DM) dominates over luminous matter in the universe. In recent years the relic abundance of DM has been extracted with good precision from cosmological measurements,  $\Omega h^2 = 0.1099 \pm 0.0062$  [1]. A favoured explanation for this DM is a new neutral and stable weakly interacting particle. A variety of candidates in extensions of the standard model have been proposed [2]. The best motivated candidates are those that arise in models constructed to solve the electroweak symmetry breaking problem. This includes: the Majorana neutralino in either the minimal supersymmetric standard model (MSSM), its singlet extensions such as the NMSSM or nMSSM [3] or in GUT-scale supersymmetric models; the right-handed Dirac neutrino in models of warped extra dimensions or in models with left-right symmetry [4]; the gauge bosons or scalar photons in universal extra dimension models [5,6]; the gauge bosons of the little Higgs model [7]; the right-handed sneutrino of supersymmetric models [8]; the scalar in extensions of the standard model [9]. To this extensive list one should add new phenomenologically inspired DM candidates [10] as well as candidates with super weak interactions such as the gravitino [11].

The single measurement of the relic abundance, although precise, is not enough to elucidate the nature of dark matter and distinguish the various candidates. For this, searches in astropar-

ticle and collider experiments are being pursued actively. Direct detection experiments would unambiguously establish that a stable particle constitute the DM. For now the upper bounds on the elastic scattering cross section constrain the DM models, although some dependence on astroparticle quantities, such as the DM distribution are introduced. The indirect detection rates also depend on the DM annihilation cross section, however astrophysical sources could lead to signals that might be hard to distinguish from those of DM. For example pulsars provide a possible explanation to the latest positron excess observed by PAMELA [12].

This leaves a double challenge for dark matter studies at colliders and in particular at the LHC. The first goal is the search for the DM candidate and/or other new particles predicted in the framework of the various theoretical models. The second, if a signal is found, would be to determine the properties of the DM particles, its mass, spin and couplings. This information could then be used to infer the DM annihilation and elastic scattering cross sections. A comparison with the value of the relic abundance extracted from cosmological observations would then allow to test the underlying cosmological model. For example the relic density can be reduced by orders of magnitude in non-standard scenarios with low reheat temperature and/or late entropy production [13,14]. A comparison with (in-)direct detection rates would allow self-consistency checks and provide additional information on quantities such as the DM distribution, the propagation models,

etc... How well the properties of DM can be determined strongly depend on the particle physics model. Below we summarize the main results for the LHC discovery potential as well as for parameter determination in three extensions of the standard model: the MSSM, the universal extra dimensions model and a little Higgs model.

## 2. NEUTRALINO IN SUPERSYMMETRY

In supersymmetric models, DM candidates include the neutralino, the partner of the gauge and Higgs bosons, as well as the gravitino [11] and the axino [15]. We will here concentrate on the weakly interacting candidate, the neutralino, which has the richer collider phenomenology as well as the best prospects for (in-)direct detection. The neutralino DM and the collider SUSY phenomenology were first analysed in the context of a constrained model with a small and manageable number of arbitrary parameters defined at the GUT scale, the CMSSM. The model parameters are the common scalar mass,  $m_0$ , the common gaugino mass,  $m_{1/2}$ , the trilinear coupling,  $A_0$  and the ratio of the vevs of the two Higgs doublets  $\tan\beta$  as well as the sign of  $\mu$ . It has since been realised that properties of DM might not be confined to the preferred bino scenario of the CMSSM thus expanding the range of possibilities for DM searches in various GUT scale motivated models as well as in extensions of the MSSM.

At the LHC, a pp collider of 14TeV, since the direct production of DM does not leave a good signature, the best channels to detect DM particles are via the production and decay of heavy coloured particles. The signature of the DM candidate always produced in the decay chains involves observables such as missing  $E_T$  or  $p_T$ .

Supersymmetric models contain new coloured particles, the squarks and gluinos partners of the standard quarks and gluons. The cross sections for production of these particles at a hadronic collider are large, they can reach  $10^2$  pb's for sparticles of 500 GeV. Production of quarks or gauge bosons in SM processes is however orders of magnitude larger, finding efficient ways to cut the background and enhance the signal is therefore a

critical issue. Furthermore in SUSY models electroweak production of new particles, in particular the charginos and neutralinos partners of the gauge and Higgs bosons can occur. These constitute the dominant production process in scenarios where the coloured spectrum is heavy.

There are a variety of SUSY signatures at the LHC. To estimate the reach of the collider it is convenient to classify the signatures according to the number of leptons (of same sign or opposite sign) accompanying the  $E_T^{\text{miss}}$ . The reach for each event topology at the LHC with luminosity of  $\mathcal{L} = 100 \text{ fb}^{-1}$  is displayed in Fig. 1 in the  $m_0 - m_{1/2}$  plane of the CMSSM. The reach is almost 2TeV for gluinos in scenarios where squarks are very heavy (large  $m_0$ ) and can otherwise reach 3TeV for squarks and gluinos [16].

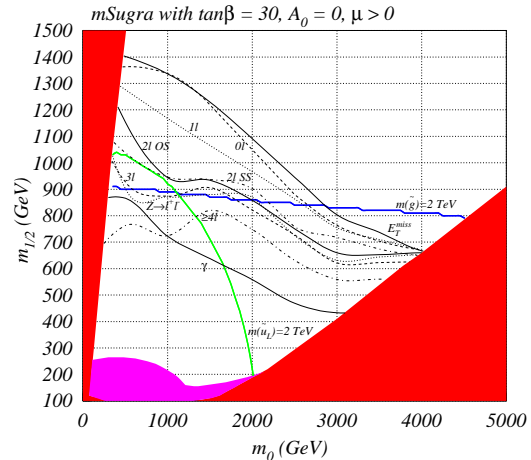


Figure 1. The LHC reach for SUSY in the CMSSM with  $100 \text{ fb}^{-1}$ . The signal is observable below the contour corresponding to each event topology, from [16].

Within the CMSSM it means that the LHC could discover SUSY in different channels in most of the region where  $\Omega h^2 < 0.11$ . This includes, see Fig. 2

- The region at low  $m_0 - m_{1/2}$  where a bino LSP annihilates into light fermions through

sfermion exchange. A fraction of this region is however constrained by Higgs searches and flavour physics.

- Part of the sfermion coannihilation region at low values of  $m_0$ .
- The region at low  $m_{1/2}$  where the bino LSP annihilates through a light Higgs resonance
- Part of the region where the LSP annihilates through a heavy Higgs resonance at large values of  $\tan\beta$ .
- Part of the 'focus point' region where the LSP is a bino/Higgsino LSP. This region is associated with heavy squarks ( $m_0 > 3\text{TeV}$ ) and only the gluino is light enough to be produced. Direct production of neutralino/chargino can also be used for SUSY discovery.

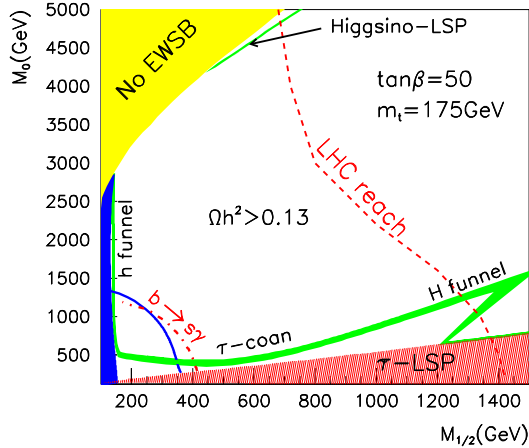


Figure 2. The regions where  $\Omega h^2 = 0.11 \pm 0.02$  (green) in the CMSSM with  $\tan\beta = 50$  and the exclusions from  $m_h > 114$  GeV and  $b \rightarrow s\gamma$ , from [17].

Note that when allowing all free SM and CMSSM parameters to vary, comprehensive fits

to available data show that the thin strips displayed in Fig.2 extend to wide regions of the  $m_0 - m_{1/2}$  plane [18,19].

The CMSSM might be a much too contrived scenario. Allowing additional parameters in GUT scale model, for example non universality of the scalars or the gauginos, or even going to the full MSSM model with parameters defined at the weak scale will open up the possibilities for DM annihilation. The LHC discovery potential in terms of squark and gluino masses should not be much affected if sparticle masses are not degenerate. The new DM scenarios include

- The bino/wino LSP which annihilates into gauge boson pairs [20].
- The bino/Higgsino LSP associated with TeV scale sfermions.

## 2.1. Determination of particle properties

For reconstructing the DM annihilation cross sections the quantities that need to be measured are the mass and couplings of the LSP, the mass of new particles (or lower limits) that contribute to DM (co-)annihilation and the mass of any resonance that can enter the LSP annihilation.

The difficulty in determining parameters of the DM model at the LHC is the large amount of missing energy that prevents the reconstruction of a mass peak. The standard method for mass determination relies rather on measuring end points in kinematic distributions [21]. Consider the standard decay of a squark,  $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow ql^\pm\tilde{l}^\mp \rightarrow ql^\pm l^\mp \tilde{\chi}_1^0$  with a signature in lepton pairs, quarks and  $E_T^{\text{miss}}$ . The upper edge of the  $ll$  distribution and both edges of the  $llq$  and  $lq$  distributions depend on the mass differences of the sparticles occurring in the decay chain, for example

$$m_{ll}^{\text{max}} = \sqrt{\frac{(m_{\tilde{\chi}_2^0}^2 - m_{e_R}^2)(m_{e_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{e_R}^2}}. \quad (1)$$

Case studies have shown that the precision achievable on the mass differences is typically at the few per-cent level [21]. This assumes that the particles in a decay chain are correctly identified which might require making some assumptions on the theoretical model. Combining this

method with cross sections measurements can improve the parameter determination [22].

The precision that could be achieved on a collider prediction of the relic abundance,  $\Delta\Omega/\Omega$ , was studied in a few generic scenario and benchmark analyses were performed for both ATLAS and CMS.

In CMSSM scenarios where the LSP is a light bino, annihilation into fermion pairs through sfermion exchange dominate together with bino/stau coannihilation. The relevant parameters are the LSP mass, the LSP couplings and the slepton masses. It was shown that to have a 10% precision on a collider prediction of the relic abundance would require a precise measurement of the mass difference  $\Delta(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})$  (at the % level) while other parameters of the neutralino sector ( $M_1, \mu, \tan\beta$ ) need to be measured at the 10% level [23]. A study of a benchmark point (SPS1a') which belongs to this class of scenario was performed by two groups for the LHC. In [24], the endpoint methods mentioned above was used to reconstruct the four masses  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}, \tilde{q}$  in squark decays. The complete determination of the neutralino sector also requires measuring the chargino mass and extracting  $\tan\beta$  from the Higgs sector. Furthermore the mixing in the stau sector which also influences the neutralino couplings is determined from the leptonic branching fractions  $Br(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l)/Br(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau)$ . The precision achievable with  $\mathcal{L} = 300\text{fb}^{-1}$  is  $\Delta\Omega/\Omega \approx 20\%$ . Similar results were obtained in [25]. Improving the determination of the neutralino and stau masses as well as the neutralino couplings as could be done at the ILC would drastically reduce the uncertainty in the  $\Omega h^2$  prediction to the few percent level [25]. For these scenarios the collider prediction for the elastic scattering cross section are expected to have almost an order of magnitude uncertainty.

An even more challenging scenario is the one where the LSP is a mixture of bino and Higgsino. In the CMSSM this means that scalars are very heavy while in the general MSSM such scenarios can occur also for a (sub-)TeV scale sfermion sector. The sfermion sector is not needed for DM annihilation since the self-annihilation of the

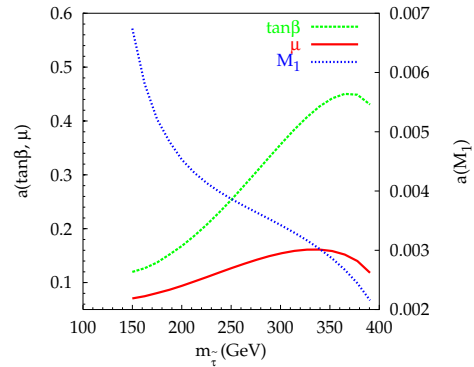


Figure 3. Required precision on  $\tan\beta, \mu$  (left axis) and  $M_1$  (right axis) for a 10% precision on the collider prediction of  $\Omega h^2$  in CMSSM bino scenarios, from [23].

bino/Higgsino into W pairs through chargino or boson exchange is efficient enough. The annihilation is governed by the bino/Higgsino fraction of the LSP which in turn depends strongly on  $M_1$  and  $\mu$ . To make a 10% prediction of the relic abundance would require to know these two parameters at the 1% level. This level of precision is a real challenge for the LHC. In this scenario the gluinos are the only coloured particle that can be produced. The gluinos decay into quarks and heavy neutralinos/charginos which in turn decay into leptons and the LSP. In a benchmark study done for ATLAS [26], it was shown that exploiting end point measurements the gluino mass as well as the mass difference between neutralinos and the LSP could be determined with a 10% accuracy. This clearly leaves a large uncertainty in the prediction of  $\Omega h^2$ , roughly a factor 4 [26].

Finally we comment on the importance of knowing the complete Higgs spectrum. Consider for example a simple extension of the MSSM with one additional singlet superfield, the NMSSM. This model contains an extra neutralino as well as new scalars. Because of efficient neutralino annihilation through a scalar resonance, one finds that  $\Omega h^2 \approx 0.1$  in regions of parameter space where one expects  $\Omega h^2 \approx 1$  in the CMSSM. After the measurement of SUSY parameters at the

LHC one would likely conclude that the collider relic abundance does not match the cosmological measurement. It would be difficult to differentiate the non-standard cosmological scenario from a new particle scenario unless the new scalar is discovered and that is challenging [27].

### 3. UNIVERSAL EXTRA DIMENSION MODEL

Models with extra dimensions offer an alternative solution to the hierarchy problem. In the minimal universal extra dimension model (MUED) all fields propagate in the bulk. Each SM particle is accompanied by a tower of KK particles, the new particles have the same spin as the standard ones. The DM candidates are either the first KK level of the hypercharge gauge boson,  $B^1$  or the KK graviton. We will consider only the former possibility since the graviton has small detection rates. The DM being a gauge boson typically annihilates more efficiently than the neutralino in supersymmetry with important annihilation channels into  $f\bar{f}$ . A relic abundance within the range determined by WMAP requires, assuming the standard cosmological scenario, a rather heavy  $B^1$  in the 500-900 GeV range [28,29]. A lighter DM implies a low relic abundance. One feature of this model is that the annihilation into light fermions in particular  $e^+e^-$  is not suppressed, favouring a large indirect detection rate for positrons. A typical signal at LHC is the production of heavy quarks decaying into a gauge boson and a quark, the leptonic decay of the neutral gauge boson leads to a signature into 4 leptons and  $E_T^{\text{miss}}$ . In this channel the LHC discovery reach is the TeV scale [30]. The cascade decays of KK or SUSY particles are very similar, one difference is that the KK particles are almost mass degenerate so that the outgoing fermions in the cascade decays can be very soft. More importantly the spin of the new particles differ by an half-integer in the two models. Different asymmetries have been proposed for spin identification at colliders [31]. An explicit example on how to use angular correlations to differentiate the fermionic gluino in SUSY from the KK gluon was presented in [32]. Note that the production of new reso-

nances, for example a  $Z^1$  decaying into fermions offers a distinctive signature of this model as compared to SUSY.

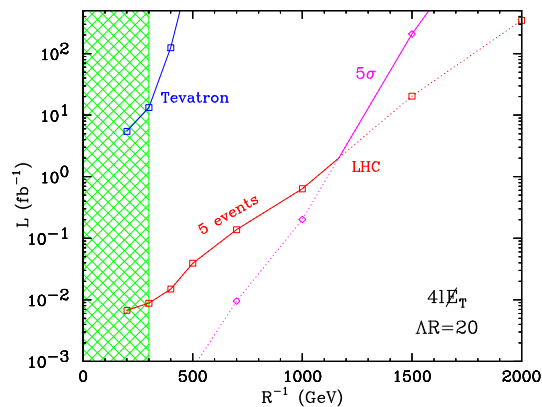


Figure 4. Luminosity required at LHC for a  $5\sigma$  signal in the  $4l + E_T^{\text{miss}}$  channel in the UED model, from [30].

### 4. LITTLE HIGGS MODEL

As a final example, consider the little Higgs model where the Higgs is a pseudo Goldstone boson originating from the spontaneous breaking of a global symmetry at a higher scale. The global symmetry protects the Higgs mass from large corrections. Strong constraints from electroweak precision observables can be avoided by imposing T-parity. The model contains new heavy gauge bosons as well as heavy top quarks (both T-odd,  $T_-$  and T-even,  $T_+$ ). The DM candidate is the lightest new heavy neutral gauge boson  $A_H$  that annihilates preferentially through Higgs exchange into W pairs [7]. The minimal version of this model, called the littlest Higgs model has only 3 free parameters: the Higgs mass, the mass of the heavy photon and the mixing between standard and heavy quarks. Because of electroweak constraints the spectrum is rather light, with  $m_{A_H} < 300$  GeV and  $m_{T_+} < 1$  TeV. The production of heavy quarks which further decay into top quarks and the heavy photon is therefore quite

large. A determination of the mass of the  $T_+$  quark as well as some combination of the Higgs, DM candidate and  $T_-$  quark masses are enough to overconstrain the model and make a "LHC prediction" of the DM relic abundance with a precision of 10% even without measuring precisely the mass of the heavy photon [33].

## 5. CONCLUSION

Understanding the nature of dark matter is an exciting challenge for the LHC. While the prospects for discovering physics beyond the standard model at the TeV scale are excellent, a precise determination of the properties of the DM particle, to the level where the theoretical predictions of DM observables reach the precision of the cosmological measurements is much more difficult.

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